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ABSTRACT

Students have well-formed but incorrect theories of simple motion. As children, they interpret many phenomena related to motion before encountering any formal science education. Since most adults have misconceptions, children's questions are not answered correctly, so the misconceptions persist. Thus, every science teacher must face the prospect that their students have serviceable misconceptions about the phenomena being studied. Yet the prototypical science course ignores all preconceptions and develops the science "de novo." Likewise, psychology of learning is largely concerned with original learning, not relearning or unlearning. Both psychologists and science educators need to ask not what should be done when the learner is not a tabula rasa, but is burdened with half-truths and conflicting concepts. Various misconceptions about motion held by students are discussed. A framework is presented for interpreting students' responses to problems involving motion, and implications for physics instruction and for cognitive psychology applications to science education are discussed. (Author/JN)

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The Relation of Knowledge to Problem Solving, with Examples from Kinematics*

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Abstract

Students have well-formed but incorrect theories of simple motion that must be changed or replaced by instruction in physics. The various misconceptions about motion are discussed. A framework is presented for interpreting students' responses to problems involving motion. Implications for physics instructions are discussed, as well as implications for the application of cognitive psychology to science education.

The Relation of Knowledge to Problem Solving,

with Examples from Kinematics

Applications of cognitive psychology to science education have recently concentrated on classical physics. Studies have been made in several laboratories of the differences between novices and experts in their ability to solve problems in the physics of motion (Larkin, et al., 1980; Clement, 1978, 1979; Chi, et al., 1979). In our own work (Caramazza, et al., 1980; McCloskey, et al., 1980) we were struck by an important fact that must be faced by any cognitive account of how persons learn classical mechanics, as this branch of physics is called. Students do not come to the study of mechanics with a blank slate. They come with prior experience and with a good practical understanding of how objects move. They usually have some idea about the general principles underlying that motion. Unfortunately in most cases they are not quite right, and in many cases they are quite wrong.

This simple fact surprised us; we were amused by the bizarre answers students gave to seemingly simple problems. We were startled to find a student who thought that a pellet impelled through a curved tube would continue in a curved path when it emerged from the tube. And we smirked when we were told that a pendulum bob whose supporting cable broke would continue along its original path briefly and then fall perpendicularly, "when gravity took over." We were sobered to discover that such responses are not flukes - nearly half of the students we tested had these or similar misconceptions about simple motion. These results are not unique to the Johns Hopkins University. Clement (1978) had observed similar mis-

conceptions at the University of Massachusetts, Champagne, et al. (1979) had found them at the University of Pittsburgh, Gunstone & White (1981) found them in Australia, and Viennot (1979) has found very similar results in France. (We were unaware of Viennot's work until very recently; it predated ours and reached similar conclusions.)

A little reflection suggests that "common sense" views of motion should be expected. People got around in the world, and devised successful transportation systems long before Galileo and Newton formulated the basic principles of classical mechanics. And a great many of our contemporaries manage very nicely without the straight news. After all, it is possible to play catch without being able to explain the ball's trajectory. It is also possible to drive a car without understanding acceleration. Today, most cars have two foot pedals - a "go" pedal and a "stop" pedal, with a hand lever to select forward or backward. That is all a driver ordinarily needs to know about acceleration. Most drivers interpret the accelerator as a speed control, since on a flat dry road it is nearly perfectly correlated with speed. Once in a while a driver gets the opportunity to try to control a car on icy pavement, but this is commonly considered to be a special condition involving abnormal behavior, and besides the driver is not likely to be in a mood for thoughtful contemplation of the experience. Friction is not considered in most naive accounts of motion. Indeed, we ourselves are not commonly aware that only balance and friction keep us from sliding out of our chairs onto the floor.

Motion is not the only phenomenon about which untutored people have misconceptions. Electricity is profoundly misunderstood. Andersson (1981) finds that the source - sink model of electrical power is popular.

In this model, power flows from the source to the consumer - from the outlet to the lightbulb - in the same way that water flows from pipes. Carey (1981) finds that people do not easily distinguish between heat and temperature. In the field of electronic computers, misunderstanding is vast.

In all these cases children have had to interpret the phenomenon before encountering any formal science education. And since most adults have misconceptions, children's questions are not answered correctly, so the misconceptions persist. Thus, every science teacher must face the prospect that their students have serviceable misconceptions about the phenomena being studied. Yet the prototypical science course ignores all preconceptions and develops the science de novo as if it were a new branch of mathematics. Likewise, the psychology of learning is largely the psychology of original learning, not relearning or unlearning. Both psychologists and science educators need to ask what should be done when the learner is not a tabula rasa, but is burdened with half-truths and conflicting concepts.

Many questions arise in dealing with misconceptions. Do the correct ideas modify, replace, or only overlay the old concepts? Is it necessary to demonstrate the falsity of the misconception? Perhaps the primary question is, "What is the nature of people's misconceptions?" Our own research has focussed on this basic question, although we have also examined some specific issues in the change of concepts through training.

Experimental Results

In our studies of motion concepts, two sets of qualitative problems were posed. One set concerned horizontal motion with no consideration

of gravity as the major factor. A group of 50 students answered these problems. Four of the horizontal-motion problems are shown in Figure 1, along with their correct answer (A, C, E, & G). Three variants of A are not shown.

Insert Figure 1 about here

Four of the vertical motion problems are shown in Figure 2. Several students have now been interviewed exhaustively about their responses to these problems, and to some adjunct problems invented as the need arose in the interviews. Their responses reinforce earlier speculations about the nature of their confusions.

The first set of problems consider circular motion in a horizontal plane. In three of those shown (Fig. A, C, & E), pellets or balls are impelled through curved channels; in the fourth, a tethered ball is being swung. In the first three problems, the student is to draw the path of the object as it emerges from the channel, "ignoring air resistance." In the fourth problem, the tether breaks; the ball's subsequent path is required. In all cases the correct answers are straight lines in the direction of the momentary velocity. But a surprising number of students provided curved paths. Curvature was evident in half of the paths from students with no formal instruction in physics, 1/3 from students with one high school physics course, and 1/8 from students with one or more college courses.

According to Newton's first law, the law of inertia, every object continues in a state of rest or of uniform motion in a straight line unless acted upon by a net applied force. The responses suggest that subjects

know the law of inertia in a vague way. As one subject put it, "Once a body starts in motion it tends to keep making that same motion until something else acts on it." The subject was not clear about what was meant by motion, since circular motion obviously qualified.

But there is more to it than misinterpretation of inertia. Somehow the object is imbued with a memory for past events, just like a tossed coin that "is due to come up heads" after four successive tails. If the coin can remember, why not the moving ball? Moreover, in some cases the circular paths tend to straighten over time. The curvature dies out with distance from the channel, and the curvature is initially greater for the spiral than for the C-shaped tube. The protocols also indicate, for some subjects, that the object will not only straighten out, but it will stop. This response is rare, and may be sensitive to context, for if we had put our tubes out in space, the stopping may have been avoided.

Many of the responses to these and later problems indicate a view of motion consistent with the medieval, pre-Galilean theory of impetus. According to the impetus theory, the action of an external force upon a body imparts to that body its own internal force, called impetus. Impetus is a property of that body, like its heat or weight. Impetus is the property that causes the body to move. In most versions of the theory, impetus is consumed as the object moves, and gradually dissipates, like heat. The object then either comes to rest, if on a surface, or falls straight down, if not supported. (Later sophisticated impetus theorists held that an external force was needed to change the impetus.) That the curves straighten could mean that impetus is invoked only for curved motion, and that as impetus dissipates, straight line motion is the major factor. Or the motion could be the result of two kinds of impetus—

with different rates of decay. In any case, the impetus theory is a useful guide for many practical situations, and may well be the natural theory that rational, untutored people reach as an explanation of motion.

Of course the theory is wrong in detail, but people seldom observe their environment with enough care to notice the discrepancies. For example when a baseball player hits a foul fly ball into the stands, spectators know pretty well where it will drop. But a surprising number of fans do not seem to realize that the ball will hit their eager hands with nearly the same velocity as it had at the crack of the bat. Luckily, they seldom catch the ball. Those who do, learn a valuable lesson.

Incidentally, Champagne, et al. (1979) identified their subjects' beliefs as Aristotelean, rather than as an impetus belief. In both views, any motion requires a force. In the Aristotelean view the medium in which the motion occurs transmits a continuing force from the original impeller to the object. In the impetus view, the force producing the continual motion resides in the body, as the impetus. There are several versions of the impetus theory, and there are several kinds of erroneous beliefs among our subjects. But all impetus theories hold that impetus is a property of the object. This seems to be our subjects' view. Many subjects are confused about the effect of the medium on the object, but none indicated a belief that the medium transmitted the needed continuing force. We make a point of this philosophical distinction not to demean Aristotle, but to give as clear as possible a picture of the observed misconceptions. In our view, it is not enough to know that a student is wrong, the teacher needs to know in what way the student is wrong.

The second series of problems shifted attention from the law of inertia to Newton's second law, F = ma. We used the trajectories of falling objects in the problems that tested understanding of the acceleration due to gravity. We asked one question about an object dropped from an airplane, and four questions about a pendulum bob that suddenly became disconnected. Responses to the pendulum questions were readily classified, and are most revealing. As shown n Figure 2 (from Caramazza, et al., 1980) about a quarter of our subjects respond correctly (Type 1). Persons giving Type 2 responses have the trajectories right, but the initial velocities are wrong. The Type 3's are wrong about both the initial velocities and the trajectories. The trajectories may indicate that gravity was seen as producing a velocity, not an acceleration. Type 4 respondents completely ignored the initial velocity, which was seen as having stopped when the tether broke. Type 5 subjects may have gotten confused about centrifugal force, supposing it to be dominant when the string breaks. Type 6 responses are the pure impetus responses. The object has an impetus which takes it along its course briefly, then the impetus dissipates, and gravity "takes over." When asked to draw the path of an object dropped from a plane, some of these subjects draw an inverted L; they indicated that the object initially moves in the direction of the plane, then gravity "takes over" and the object falls straight down. Anothr popular response to the airplane problem is a straight line trajectory like type 5. One subject said, "Nothing falling from an airplane drops straight down, but the reason why is because of air resistance." When asked to show what would happen in a void, the inverted L appeared.

Probably the subjects who drew the curved trajectories had at least a general idea about acceleration due to gravity. We cannot be completely sure, for some subjects also drew parabolas for the horizontal path with respect to the fixed ground, of an object thrown horizontally from a train travelling straight, at uniform velocity; the gradually straightening paths observed earlier may simply be instances of the ubiquitous parabola. Still, these subjects are able to adjust their responses to the falling objects in accordance with different starting conditions.

In summary, the responses tend to be consistent, indicating that they are driven by some kind of knowledge structure, however faulty.

Interviews. To gain a richer appreciation of the variety of misconceptions about motion, interviews were conducted with 13 college students, four of whom had had no formal physics instruction, three of whom had one course in high school; the remaining 6 had one or more college physics courses.*

The results (McCloskey, 1982) show that most of the students held some form of naive impetus conception of motion. According to impetus theory, the initial force imparts an impetus to the object. Impetus is a kind of inherent force in the object that keeps it moving. But impetus gradually dissipates, which is why objects slow down and stop if they receive a more external force. There are individual variants of the general impetus notion. In soe, impetus must dissipate below some critical value before another force can have any effect on the object, whereas in other variants, twc impetuses can add. Many

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* These studies were in progress at the time of the conference, but have now been completed and reported.

variants admit curvilinear impetus, as indicated by the expected curved path in the ball and string problem. That is objects moving in a curved path are expected to continue curving when there is no external force - the impetus in the object is of the curved variety. Generally, the curved aspect is more transient than the movement itself, for the path is expected to straighten, gradually.

Dynamic visual displays. All of our work discussed so far has involved verbal problems supported by static diagrams. Suppose a simulated display shows the students the movements that they predict. Or suppose the subject could see a variety of different movements, all but one of which is wrong. It seemed plausable that they would then be able to pick out the correct movement, or to recognize incorrect motion. So we programmed a minicomputer to display dynamic simulations of the ball and string, the pendulum, the curved tube, and the bomb falling from the plane. We showed these simulations to students, in various controlled experiments.

Alas, the answer is unequivocal. Expected motions that are physically impossible, nevertheless "look" perfectly believable. There is nothing especially compelling about the visual information. Showing the dynamic displays had virtually no effect on the subjects' judgments. We agree with the subjects; we can attest that a ball that continues curving as it emerges from the curved tube looks perfectly normal. We did notice one special effect that occurred in the plane and bomb display; as McCloskey (1982) has shown, this has to do with a perceptual illusion caused by a frame-of-reference problem, that is specific to situations with two objects

moving differentially.

The structure of scientific knowledge. A cognitive account of the problem-solving behavior of our subjects must rest on a description of their knowledge about motion. Scientific knowledge is of two sorts, knowledge of certain facts, principles and laws, and knowledge of procedures for applying the relevant factual knowledge to the problem situation. This is equivalent to the philosophical distinction between "knowing that" and "knowing how." Students must know that force=mass times acceleration, and must know how to determine the force acting on a body, and the nature of the acceleration, if any.

We suppose tht a student in our studies tries to retrieve factual and procedural knowledge relevant to the problem, and then somehow constructs an answer from the retrieved data. If no data are retrieved from memory, the student lowers the criterion of relevance, and tries again. Usually, several bits of knowledge are retrieved, and the student fits them together somehow. Collins et al. (1979) said it persuasively:

> "It does not trouble people much that their heads are full of incomplete, inconsistent, and uncertain information. With little trepidation they go about drawing rather doubtful conclusions from their tangled mass of knowledge, for the most part unaware of the tenuousness of their reasoning. The very tenuousness of the enterprise is bound up with the power it gives people to deal with a language and a world full of ambiguity and uncertainty."

The way that our subjects deal with the tangled bits of knowledge that they retrieve is not clear. Those who answer the curved tubes correctly and quickly apparently look for "motion," obtain the procedure "find forces and velocities," determine that the force is 0, and the velocity is unspecified. "Motion, no force" in turn yields Newton's first law, and they respond appropriately. Others keying on "circular motion," may find "centrifugal force," "angular momentum," and other bits of no use. Some may find a vague version of the law of inertia.

The retrieved information might either be a general principle or law, or it could be a specific experience. In the detailed interviews, subjects generally explain their responses in terms of general principles. In only a few cases is a specific experience or an example reported. Probably, if both principles and experience are retrieved, principles are preferred. But the characteristics of the situation -- college professors talking to college students about obviously idealized problems -- may seem to demand justification by general principles. It may be significant that the subject who referred most to specific experiences was a middle-aged lawyer, not a student.

It is possible that students do recall specifics, but readily abstract generalities from examples. In any case, students mostly report general principles. For example, one of our subjects thinks that a swiftly moving object, when it encounters a cliff, will continue in a straight line, and then fall straight down, "when gravity takes over." That is reminiscent of the coyote in the Roadrunner cartoon. But the resemblance was not volunteered. Only the general principle was enunciated.

Nearly all of our subjects recalled some form of the law of inertia. Their difficulty was in knowing the details. About half did not know that it prescribed motion in a straight line. Most of the interviewed respondants did not know that it prescribed uniform motion. Many thought that all objects slow down and stop, if not acted upon by an outside force.

In the problems that involve gravity, the nature of gravity found many interpretations. Some merely retrieved the notion that gravity pulls things straight down. The nature of the pull was not clear to many. Some seem to understand that gravitational motion accelerates. Others thought gravity imparted a steady velocity. Some interpreted gravitational acceleration to mean that the pull of gravity was stronger close to the ground than way up in the air. One person held this belief so strongly that given a choice between being hit on the head by an object dropped from one inch above the head, or one dropped from 10 feet above the head, opted for the 10-foot drop.

When two forces are acting on an object, a procedure must be evoked to effect some kind of resolution. Some subjects chose an average or compromise, in the manner of vector resolution. Others chose a dominance procedure, in which the stronger force acts alone, while the weaker force has no effect. We must be careful here, since the second force in these problems was usually gravity, which may be unique for these students. The fact is that some students thought that an object moving horizontally in the presence of gravity -- the pendulum, the object dropped from a plane, and various objects propelled off various cliffs -- would first exhibit horizontal motion and then fall straight down. This result requires the decaying impetus view of the horizontal motion and the dominance procedure for dealing with competing components of velocity.

Some of the interviewees distinguished between a ball that was thrown (horizontally) off a cliff, and a ball that was carried at a constant velocity to the edge of the cliff and let go. The carried object underwent what might be called passive motion, which apparently doesn't gather any impetus, since those objects were expected to fall straight down. By contrast, the thrown or impelled objects were seen as traversing parabolas, or inverted L's. In either case, they had acquired impetus. The parabola indicates vector resolution; the inverted L represents the dominance view.

Some subjects correctly applied the technique of vector resolution but did not know that the vectors represented instantaneous velocities. They interpreted the vectors as trajectories. Others interpreted acceleration as velocity.

One reason for the difficulty most people have in interpreting natural motion, is that they have trouble idealizing. This is especially the case when the ideal case is not normal, or prototypic, but is profoundly abnormal, such as the ideal of frictionless motion. People usually reserve their simplest explanations for the most commonly observed events, leaving the complications for the rare events. Thus, a surface offering an excess of friction is "sticky", a surface providing relatively little friction is "slippery." It takes expert instruction accept the view that infinite slipperiness is ideal. Similarly, a container without any air or other content is not empty; it is viewed as containing a vacuum. This difficulty is quite natural. People view the world in terms of categories. Usually the prototypical category member is also the norm or mode. The prototypic chair has a seat, a back, and four straight legs. Most chairs are like that. But the prototypic motion is probably a thrown ball

or a dish knocked off the table, or even worse, a moving automobile. None is anywhere near the Newtonian ideal. Students must be taught that an extreme is really ideal. It does not come naturally.

A related problem is the human penchant for distorting truth in order to fit it into one's existing presuppositions. This is more of a problem when the truths are value-laden, as in the political arena, but it is also a general cognitive problem. A student of the impetus persuasion might, upon encountering Newton's first law, decide that this meant that impetus did not die out, but was permanent. Well, isn't that good enough? It will serve in many cases, but it could fail in Clement's spaceship problem. A ship in intersteller space is "drifting" in a path depicted as left to right across the page. At a certain point, a rocket on the object's side is turned on for a brief finite time, providing a force perpendicular to the path (toward the bottom of the paper, say). A believer in permanent impetus might choose the popular response of a straight line toward the lower corner of the page while the rocket is firing, returning to a left-to-right hoizontal path when the rocket ceases, whereas in fact there is no return, the ship continues along the path followed while the rocket was active.

The work described here is a small part of a growing body of information about student misconceptions. In the field of motion, Trowbridge and McDermott (1981a,b) showed that adults have trouble with the concepts of velocity and acceleration. Piaget (1970) reported that movement and speed are poorly understood by children. Champagne et al (198) found that many college students believe that objects fall at a constant speed. Clement (1978) has described a number of problems with which students have difficulty.

Information about procedural knowledge has been obtained through a comparison of novices and experts solving problems (e.g. Chi, Feltovich & Glaser, 1980; Bhaskar & Simon, 1977; Larkin & Reif, 1979, Larkin, McDermott, Simon & Simon, 1980; Novak & Araya, 1980). Larkin et al report that experts work forward from the quantities given in the problems to the desired unknown, whereas novices work backward from the unknown to the givens. Also experts can quickly categorize a problem (e.g., "Oh, that's an energy problem.") and have a standard procedure for dealing with each category of problem.

Of what use are next steps characterizations of popular misconceptions? In our view, teachers must address the popular views as a part of instruction in the scientificually correct view. Cognitive psychologists now believe that very little is forgotten. New information either overlays or modifies old information. It is easy to overlay an incorrect law of inertia by the correct one. The other two postulates of motion can be treated in the same way. Will that suffice, or should the students be told why, or in what sense, their naive postulates are inadequate? If old ideas neither die nor fade away, the teacher cannot simply say, "Forget all your preconceptions about motion and learn new principles." The student cannot follow that advice. If the student merely learns the new information of Newton's laws - then when he meets an unfamiliar problem, both the new and the old facts are likely to be retrieved. To prevent the old information from being used, the misconceptions must be altered in some way, by demonstrating their falseness. Since the misconceptions are the products of years of everyday experience, it seems to us that a good way to solidify the correct information and to show the error in the misconceptions, is to require the student to explain everyday natural phenomena in terms of the correct

fundamental principles. It would probably be better for the student to do it himself rather than to hear about it, but he needs careful guidance so that in the process of developing the correct explanations he makes as few errors as possible along the way. A fine example of this strategy is described by Minstrell (1981) who actively confronts the misconceptions about forces and motion, and whose students show long-term retention of the correct view.

Another possibility is to provide better experiences. On the assumption that misconceptions like impetus come from incomplete or incorrect perceptions of common events, complete accurate perception might help the student to accept the new concepts. For example, acceleration is not readily appreciated. A slow motion (possibly animated) display could show how gravity affects falling objects. A display that could be controlled by the student would be especially attractive. The student could then watch the effect of different gravities: Earth, moon, Jupiter, or some hypthetical space station.

Of course one function of laboratory experiences is to provide such insights. But another function of the labs that usually accompany science courses is to teach scientific method and lab techniques. It is important to impart an appreciation of how science proceeds, and why precise measurements are necessary. Unfortunately for the content, method and technique are usually paramount and the students may fail to appreciate the facts being rediscovered, because they are concentrating on the methods. It seems important to use laboratory interviews both to display methods and also to provide insights.

In summary, physics courses should be designed in the knowledge that students do not correctly understand motion before the course, and may cling to the various "common sense" views that they have used all their lives, even after the course.

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Figure Captions

Fig. 1. Typical answers to problems involving horizontal motion. See Text for dtails.

Fig. 2. Typical answers to the pendulum problem. See text for details.

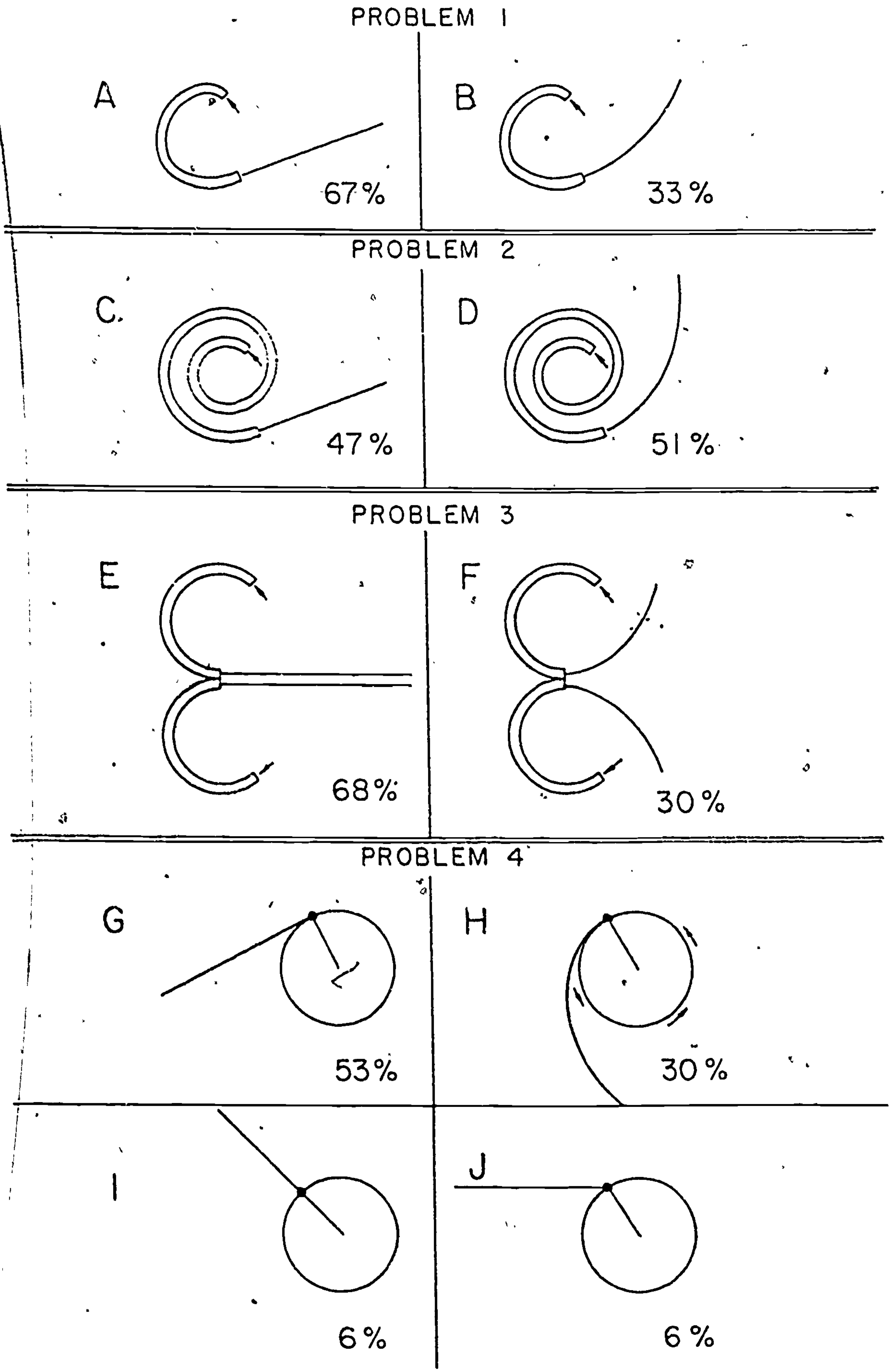
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Figure 1

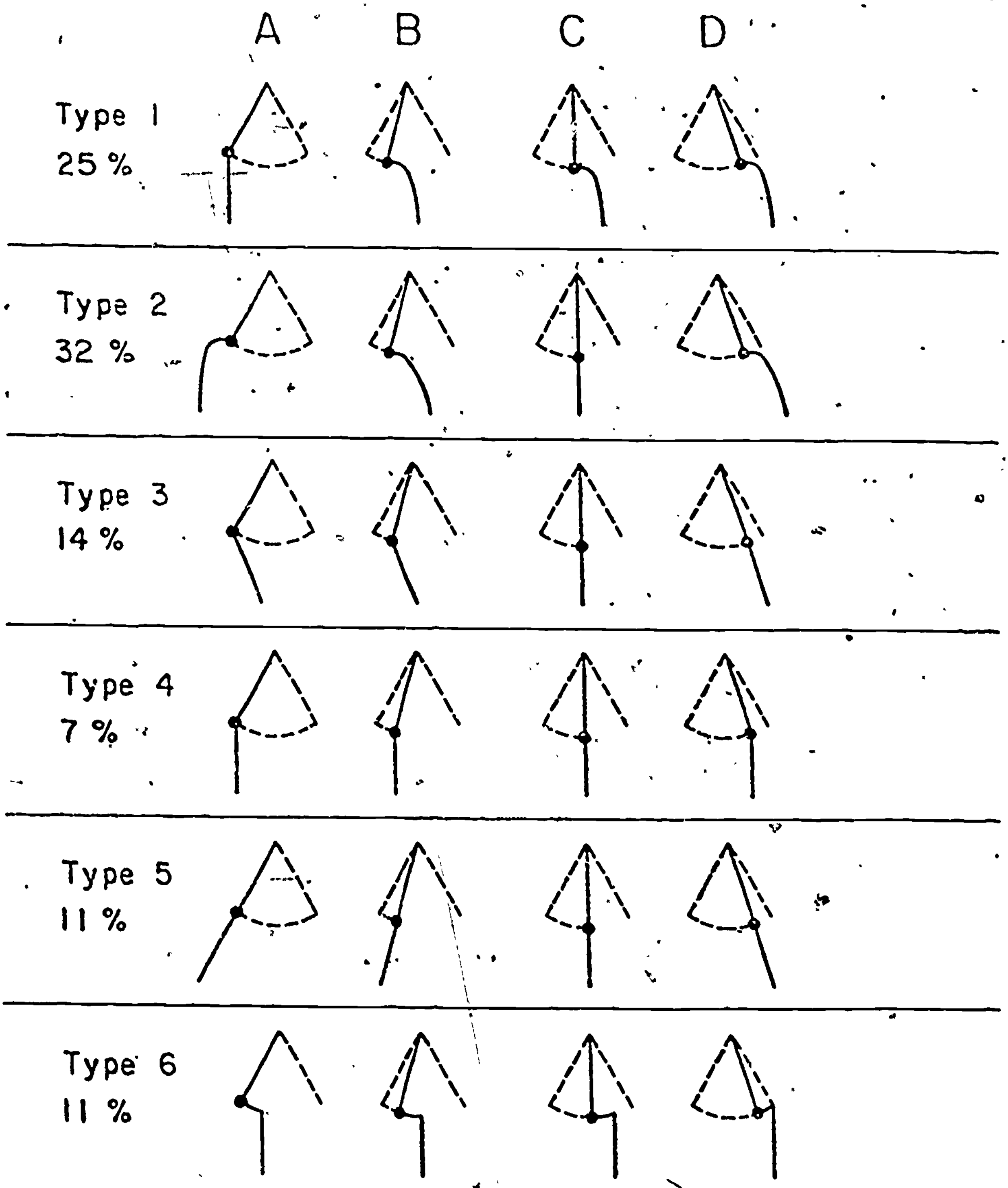

Figure 2